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ARD-227

PROGRESS REPORT NO. 3

PROPELLANT COMBUSTION STUDY

CONTRACT NO. Nonr 2[illegible](00), Phase II

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Report No. ARD-227

16 April 1959

PROGRESS REPORT NO. 3

RESONANT COMBUSTION STUDY, CONTRACT NO. Nonr 2458(00), PHASE II

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SUMMARY

Static burner testing ~~has been~~ were conducted on a small scale to discover trends which will be useful in the layout of the shrouded combustor for connected-pipe tests. Burners were tested with ~~twelve~~ 12 inlet tubes at 90° to the burner axis, inlet tubes slanted 45° upstream and 45° downstream from the 90° position, and inlet tubes at 90° to the burner axis but nominally tangential to the combustor shell.

Using the inlet tube direction which resulted in the best apparent performance (the 45° downstream inlets), the effects of burner length and exhaust configuration, fuel nozzle protrusion into inlet tube, inlet tube penetration into combustion chamber, and inlet tube length were observed. For the configuration of a 4" inside diameter burner with twelve .658" I.D. inlet tubes inclined 45° downstream, the best performance was obtained with a burner length of 30 5/8" including an exhaust expansion to 5" I.D. Fuel nozzles were flush with the inlet tube entrances and inlet tubes as nearly flush as possible with the inside surface of the combustor. Performance deteriorated as the inlet tube length was reduced from its initial length of 3 inches in 5/8" increments.

Development of the gaseous propane fuel supply system resulted in a system which was satisfactory in all respects for the static burner testing, and which is expected to be equally satisfactory for the shrouded combustor tests.

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CONTENTS

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4. LIST OF FIGURES

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1. INTRODUCTION

1.1 Background

Extensive exploratory static burner tests were conducted in Phase I of this contract in order to discover trends concering the effects of various combinations of combustor geometry on the ability of burners to support resonant combustion over wide ranges of fuel flow. This early phase of the program resulted in the development of a shrouded combustor with a maximum of 100 air and fuel inlets with the air inlets completely submerged in the combustor shell. In order to facilitate simplicity of construction, the air inlets were installed at 90° to the longitudinal axis of the combustor.

1.2 Concept

For some time there has been considerable interest in determining the effect of slanting the flush air inlets so that the blowback through the inlets would be directed downstream in the surrounding shroud. There are various reasons why this should be helpful. First, the blowback should not tend to block the inflow to the shroud. On the contrary, it may act somewhat as ejector primary flow to increase flow through the shroud. Second, the possibility exists that the combustor pressure rise at the head end might be increased by inflow through the inlets that is directed towards the head end of the combustor. Third, in exploring other simple but untried inlet directions into the combustor, a direction of inlet might be found which gives a significantly greater fuel flow range at which resonance is sustained.

1.3 Approach

Because of the rather difficult construction problem involved in a shrouded multiple inlet combustor with slanted air inlets flush with the outer surface of the combustor shell, some initial comparative static tests of an unshrouded burner with simple hardware were conducted. These tests compared the thrust and pressure rise across the head end of the combustors with twelve air inlets aligned as follows: (1) at 90° to the longitudinal axis of the combustor, (2) slanted downstream at 45° and (3) at 90° to the longitudinal axis of the combustor but nominally tangential to the combustor shell (swirl-inflow). The purpose of these tests was to look for trends that might help in the layout of the next shrouded combustor configuration, recognizing of course that there is a big jump from the static operating situation to that in which the burner is shrouded and the air inlets are made flush with the shell.

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It is recognized that many additional variations of static burner configurations could be conceived and tested, but the scope of this investigation necessarily requires that the variations be limited to a few simple configurations which will provide a good quantity of data to show trends. This progress report describes the characteristics of the fuel supply system, the test instrumentation, the static burners tested, and the trends and conclusions derived.

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2. DISCUSSION

2.1 Propane Fuel Supply System

The fuel supply system is shown in the Figure 1. The function of the heating tank in which the propane cylinder is immersed is to heat the propane, thus raising its vapor pressure and, consequently, raising the fuel supply pressure. Liquid tap propane cylinders were used in preference to gas tap cylinders in order to obtain a more stable fuel supply pressure. With a gas tap, a large volume rate of gas flow out of the cylinder occurs when the burners are operating. This requires a large rate of gas production in the cylinder, resulting in constantly decreasing cylinder pressure, since the temperature of the entire cylinder of propane cannot be raised quickly enough to provide the required latent heat of vaporization to support gas production requirements. With a liquid tap, on the other hand, a relatively small volume rate of liquid flow out of the cylinder occurs, and gas production occurs readily, thus maintaining constant cylinder pressure. Since the interpretation of the readings of the Fischer-Porter Flowrator Meter used to measure gas flow rate is quite sensitive to gas pressure, the liquid tap fuel system was essential to the accuracy of the test data.

The direct weight rate of propane flow was determined by means of the weight scale on which the propane cylinder and its heating tank were mounted as shown in Figure 1. From the valve mounted on the propane cylinder, the liquid fuel was led through a 200 psi relief valve and through a short length of flexible hose to the coil heating tank; there the liquid propane was converted to gas in the coils immersed in hot water. A supply pressure gauge and a flow regulating valve were mounted downstream of the coil heating tank. From the flow regulating valve, gaseous propane was led to the Fischer-Porter variable-area flowmeter where its pressure and temperature were measured at the meter outlet; it then went to the three-way valve.

The three-way valve was not a regulating valve, and it was used only to provide a quick means of shutting off fuel to the resonant burner or to substitute compressed air for fuel in order to scavenge and cool the burner. When a short air blast was required to start a burner resonating, it was introduced by means of the three-way valve.

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2.2 Static Burner Variations

Static burner testing commenced with a burner configuration which had been previously tested in early phases. It consisted of a 26" length of 4" I.D. pipe of 1/4" wall thickness, closed on one end, with twelve air inlet tubes installed at 90° to the axis of the pipe. From this starting point, inlet tube configurations were changed, burner lengths were varied, burner exit characteristics were investigated (expansion at exit, contraction at exit, and constant area exit), and the degree of penetration of the fuel nozzles into the inlet tubes was varied.

In addition to the 90° inlet tubes, the following directions of inlet tube inclination were tested:

a) inlet tubes inclined 45° upstream (inclined 45° toward the head end of the burner from the 90° position.)

b) inlet tubes inclined 45° downstream (inclined 45° toward the exhaust end of the burner from the 90° position.)

c) inlet tubes at 90° to the plane of the burner axis, but introduced nearly tangentially into the burner.

Figure 2 shows the layout of each basic inlet configuration tested, the basic burner dimensions, the dimensions of the end bell and nozzle used to create a burner exit expansion and contraction respectively, and the dimensions of the fuel nozzles. Note that combustion pressure was measured at several points across the burner head only.

2.3 Results

2.3.1 Comparison of Various Burner Inlet Configurations

The inlet tube configuration in which the tubes are inclined 45° downstream gave performance superior to those of the tangential, the 90°, and the 45° upstream inlet tube installations, considering the combined requirements of high combustion pressure, high thrust, short burner length, ease of starting resonant combustion and fuel flow range at which resonance was maintained. Figures 3, 4, and 5 show performance comparisons. The characteristics of the other (tangential, 90° and 45° upstream) inlet tube

directions are discussed below relative to the 45° downstream inlet tube installation.

For the sake of convenience, parameters are sometimes discussed relative to fuel pressure rather than fuel flow. This is justified, since the fuel flow path from pressure gauge to burner is identical in every case, and the effects of fuel temperature and the pressure zone into which the fuel sprays are thought to be slight.

2.3.1.1 Tangential inlet

The thrust obtained with the tangential inlet burner at its maximum fuel flow was approximately equal to that obtained with the 45° downstream inlets at the same fuel flow. This thrust was achieved with an average burner head pressure of barely 1" H_2O gauge pressure, whereas the 45° downstream inlet configuration had an average burner head pressure of 17" H_2O gauge pressure at the same thrust. However, at 57" burner length this configuration still could not equal the fuel flow range over which the 45° downstream inlet configuration with 30 5/8" length would resonate. Nor could it match the maximum thrust obtained. The effect of reducing the length of the tangential inlet burner to 39 5/8" was to raise the burner head pressure sharply, reduce the thrust slightly, and reduce significantly the fuel flow range at which the burner would resonate. No data were recorded at 30 5/8" burner length with tangential inlets because it was too difficult to start resonance.

2.3.1.2 45° Upstream inlet

Appreciably lower thrust and burner head pressure were obtained with this inlet than with the 45° downstream inlet at 30 5/8" burner length, and the fuel flow range to support resonance appeared reduced. Increasing the burner length to 40" resulted in a mild thrust decrease, considerable pressure increase, and an increase in the fuel flow range for resonant combustion.

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At 45 5/8" length, the thrust was equivalent to that of the 30 5/8" length, and pressure decreased slightly from that of the 40" length. Again the fuel flow range for resonance was increased with increased burner lengths, and resonance would begin automatically at 6PSIG fuel pressure.

2.3.1.3 90° Inlet

At 30 5/8" burner length, the 90° inlet burner provided thrust approximately equal to that of the 45° downstream inlet but at a lower pressure. These effects held at fuel flow rates less than 70 lbs/hr. In the range of 70 to 75 lbs/hr fuel flow, both thrust and burner head pressure began to fall off, and a maximum for each was experienced at 80 lbs/hr fuel flow, corresponding to a fuel pressure of about 125 psig. Beyond this fuel flow, both thrust and pressure were reduced, and it is concluded that this burner has a deteriorating change of characteristics near this point. Resonance began automatically at 22 psig fuel pressure, and rich-out occurred at 142-145 psig.

2.3.2 45° Downstream inlet

2.3.2.1 Effect of burner length and exhaust diameter

The 45° downstream inlet configuration was tested with several combinations of burner length and exhaust diameter, as shown in the table which follows and in Figures 7 and 8. Of these combinations, the 30 5/8" burner length, including end bell, gave the highest thrust but had a slightly lower burner head pressure than the 25 5/8" length with end bell.

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TABLE 1

CHARACTERISTICS OF VARIOUS 45° DOWNSTREAM INLET BURNERS

Burner Length	Exhaust Fitting	Exhaust Diameter	Thrust @ 80#/HrF.F.	Arith.Ave. Head Press. @80#/HrF.F.	Resonant Starting	Lean-Out Fuel Press.	Rich-Out Fuel Press.
25-3/8"	Reducer	3 1/2"	----------	-----------	No. Res.	-----------	-----------
26"	None	4"	5.2 lbs.	16.3"H_2O	Air Req.	25 psig	145 psig
25-5/8"	End Bell	5"	5.2	16.7	Air Req.	20	> 171
30-1/8"	Reducer	3 1/2"	4.3	14.2	Air Req.	< 39	150
30-5/8"	End Bell	5"	6.2	15.6	Auto@45psi	30	> 175
36-1/8"	Reducer	3 1/2"	3.8	13.0	Air Req.	< 39	175
40"	None	4"	4.5	12.3	Undet.	< 40	> 152
45-5/8"	End Bell	5"	5.5	13.0	Undet.	< 33	> 160

2.3.2.2 Effect of fuel nozzle penetration into inlet

Using the burner of 30 5/8" length including end bell, various positions of fuel nozzle penetration with respect to inlet tube entrance plane were investigated. The effect of the fuel nozzle position is quite pronounced, since the fuel jet into the air inlet acts as an injector (jet pump) to aid charging of the burner with fresh air during the intake portion of the combustion cycle. Four fuel nozzle positions were tested, as follows, using 3"length inlet tubes.

a) Nozzle 1/4" outside plane of inlet tube entrance

b) Nozzle in plane of inlet tube entrance

c) Nozzle projecting 1/4" into inlet tube

d) Nozzle projecting 1/2" into inlet tube

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In cases (c) and (d), resonant burning would not start without an air blast, so complete data were not taken. Placing the nozzle 1/4" outside the plane of the inlet entrance (a) resulted in a small decrease of thrust and pressure relative to the values obtained with the nozzle in the plane of the inlet entrance (b) as shown in Figure 9.

2.3.2.3 Effect of inlet tube penetration into combustion chamber

As maybe seen from Figure 2, bushings were provided into the combustion chamber of the 45° downstream inlet burner so that the inlet tubes could be moved along their axes to allow the degree of penetration into the combustion chamber to be varied. The inlet tubes were held in position in the bushings by cap screws. Note also that the bushings themselves projected a small distance (approximately 1/2" to 3/4". See Figure 2) into the combustion chamber.

The effect of inlet tube penetration was studied with five positions of inlet tube, as follows;

(a) inlet tube end flush with end of bushing

(b) inlet tube protruding 1/4" beyond end of bushing

(c) inlet tube protruding 1/2" beyond end of bushing

(d) inlet tube protruding 3/4" beyond end of bushing

(e) inlet tube scarfed 45° on the end so as to make the plane of the end parallel to the longitudinal axis of the burner.

In general, the best performance was obtained with the inlets flush with the ends of the bushings or protruding 1/4", and performance deteriorated as the inlets were moved inward. Case (e), however, gave the worst performance (See Figure 10).

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With the plane of the inlet tube end parallel to the axis of the burner, thrust was significantly lower over most of the fuel flow range than with the plane of the end at 45° to the burner axis, despite the fact that in cases (b), (c), and (d) the actual penetration into the combustion chamber was greater.

2.3.2.4 Effect of inlet tube length

Starting with an inlet tube length of 3", the tubes were reduced to 2 3/8" length, then scarfed 45° on the inner ends, and then reduced to 1 11/16" length. Performance deteriorated significantly as the length was reduced as may be seen in the plot of Figure 11. Comparing the 1 11/16" inlet condition with the scarfed end condition where one side of the tube was 2 3/8" long and the other side was 1 11/16" long, the only difference in performance was that the scarfed condition gave a larger fuel flow range for resonant combustion. In the scarfed condition, the inlet tubes were so oriented that the plane of the end of the tube was parallel to the axis of the burner.

2.3.3 Efficiency of Combustion

In terms of percent combustibles in the burner exhaust, the resonant burner appears to have very good combustion efficiency, based upon a preliminary check. A single-point check with a Johnson-Williams combustible gas indicator showed about 1% combustibles in the exhaust (roughly comparable to a Diesel engine).

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3. CONCLUSIONS

The foregoing results indicate a number of significant conclusions relative to the static resonant burners, as cited below.

1. For any given burner configuration, thrust varies approximately linearly with average pressure across the burner head over most of the fuel flow range, but not necessarily with fuel flow. Near [illegible]-out, the thrust begins to lag, and may even reverse with some configurations.

2. For a particular burner, each direction of inlet tube into the combustion chamber provides a characteristic of thrust vs average burner head pressure peculiar to that direction of inlets, and the effect of inlet direction on burner performance is very strong.

3. For a given burner configuration, lengthening of the burner results in easier starting and a greater fuel flow range over which resonant combustion will occur.

4. A contracting burner exhaust results in a lower rate of change of thrust with respect to average burner head pressure, poorer starting, and a lower fuel flow range for resonant combustion than does an expanding burner exhaust.

5. Use of an expanding burner exhaust results in a greater fuel flow range for resonant combustion than with a constant area exhaust, but does not significantly affect thrust vs average head pressure.

6. Burner thrust vs average head pressure appears to be not nearly so sensitive to burner length and exhaust configuration as it is to direction of inlets. On the other hand, ease of starting and the range of fuel flow to support resonant combustion appear to be more dependent on burner length and exhaust configuration than on inlet direction.

7. The average burner head pressure required to produce a given thrust is a function of inlet tube direction, and can vary widely from one direction of inlet tube to another.

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8. The optimum location of the fuel nozzle exit is in the plane of the inlet tube entrance.

9. In general, performance decreases severely as the inlet tube penetration into the combustion chamber increases and as the inlet tube length is reduced below some optimum value (for a given burner).

10. The particular shapes of the curve of burner head pressure vs radial distance from the burner axis appears to be set by inlet tube characteristics, and appears similar to (and therefore predictable from) the shape of the curve obtained when air alone is blown through the fuel nozzles and there is no combustion.

11. For a given burner length (which for practical purposes would certainly be as short as possible), resonant burner performance is highly sensitive to inlet tube direction, length, degree of penetration into the combustion chamber, and exhaust configuration, and these areas should eventually be explored further as a means of optimizing burner performance.

12. While recognizing the necessity for an expanded future program of static burner testing to optimize performance and basic design parameters, it is recommended that a shrouded 100-inlet combustor now be built and tested to verify that the gap between a static burner with a small number of inlets and a shrouded burner with a much greater number of smaller inlets can be bridged in a practical manner.

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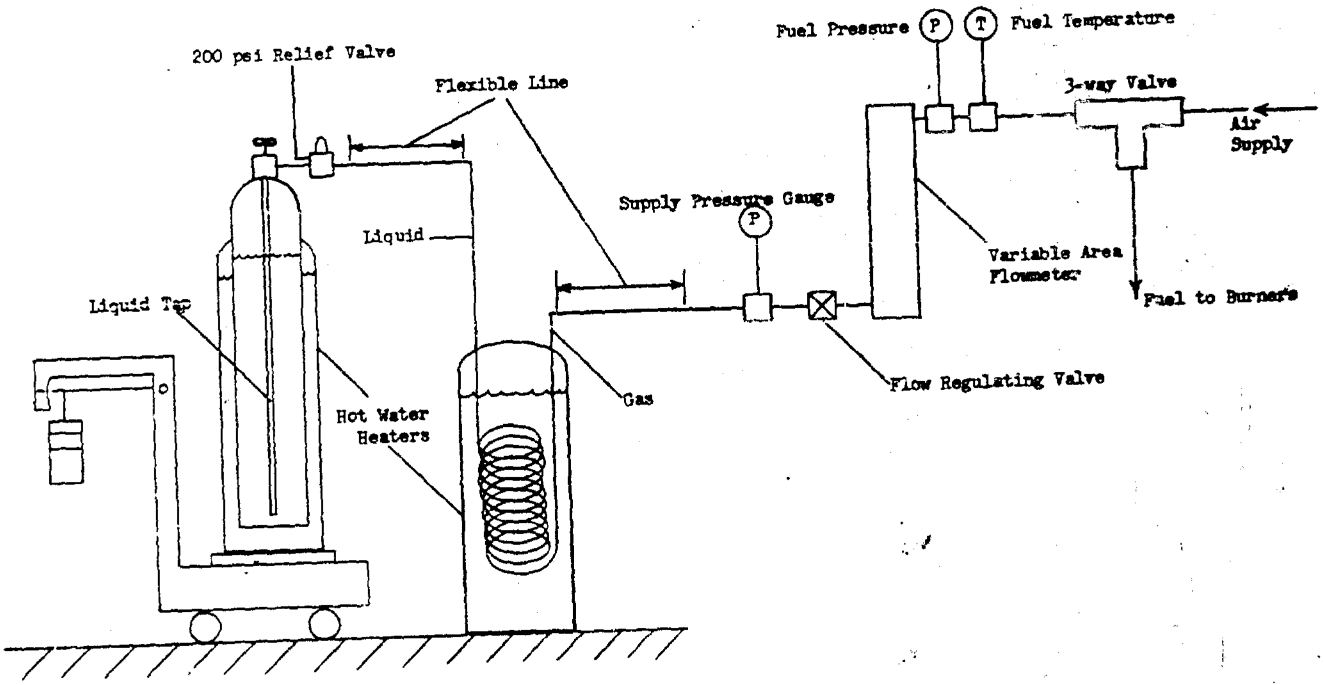

FIGURE 1: FUEL SYSTEM ARRANGEMENT

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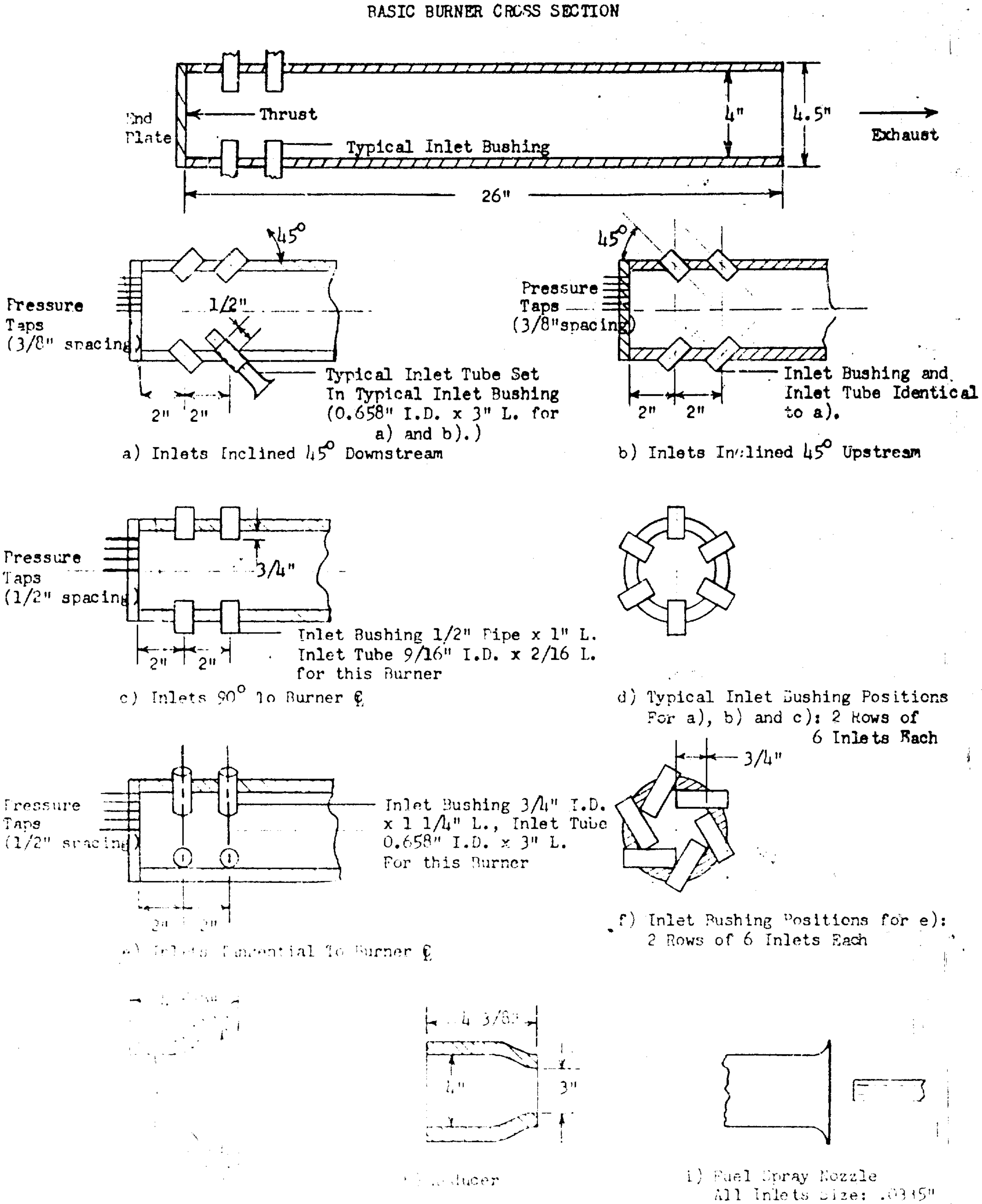

BURNER CONFIGURATIONS

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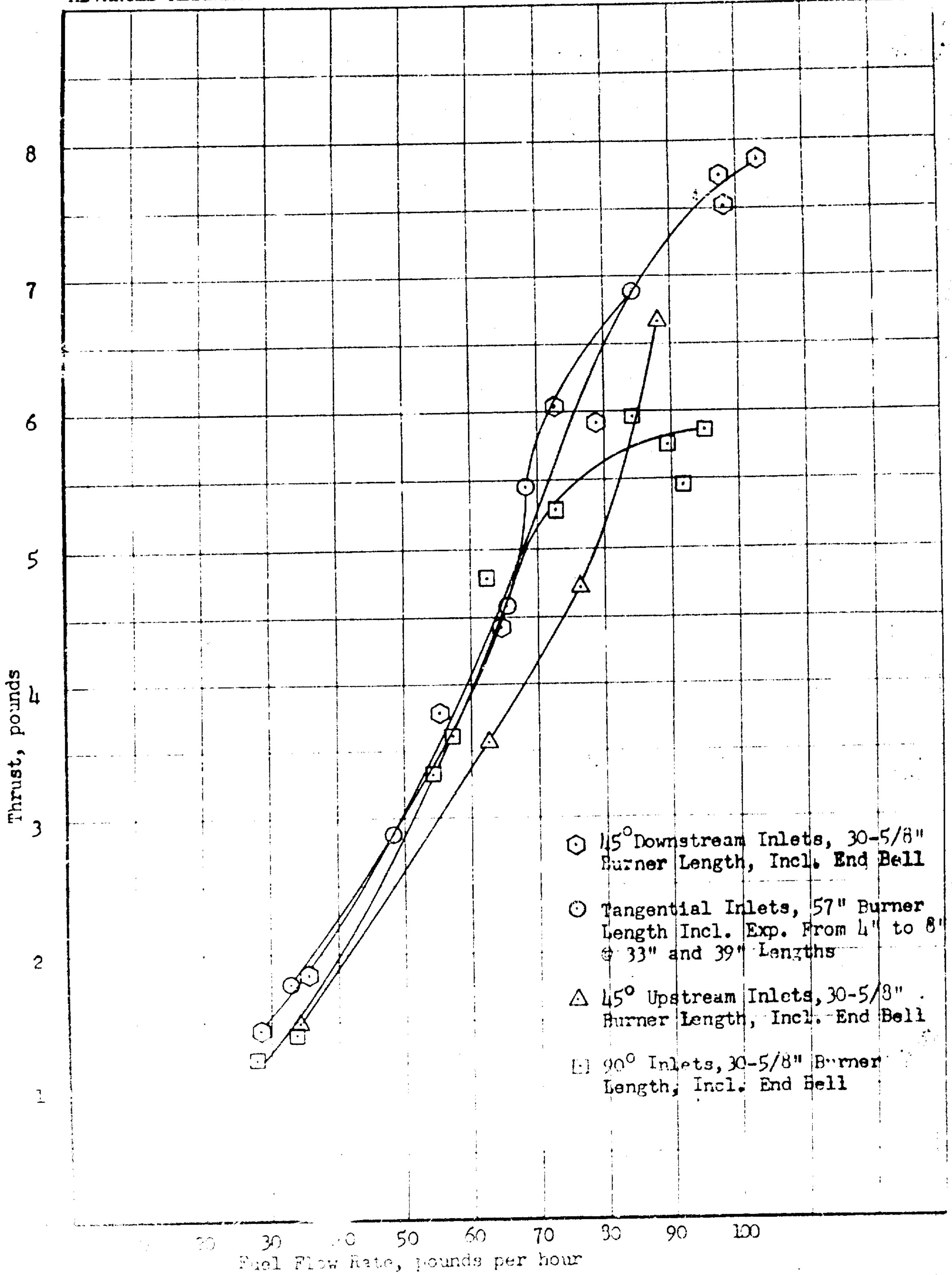

...UST VS. FUEL FLOW RATE, VARIOUS INLET TUBE DIRECTIONS

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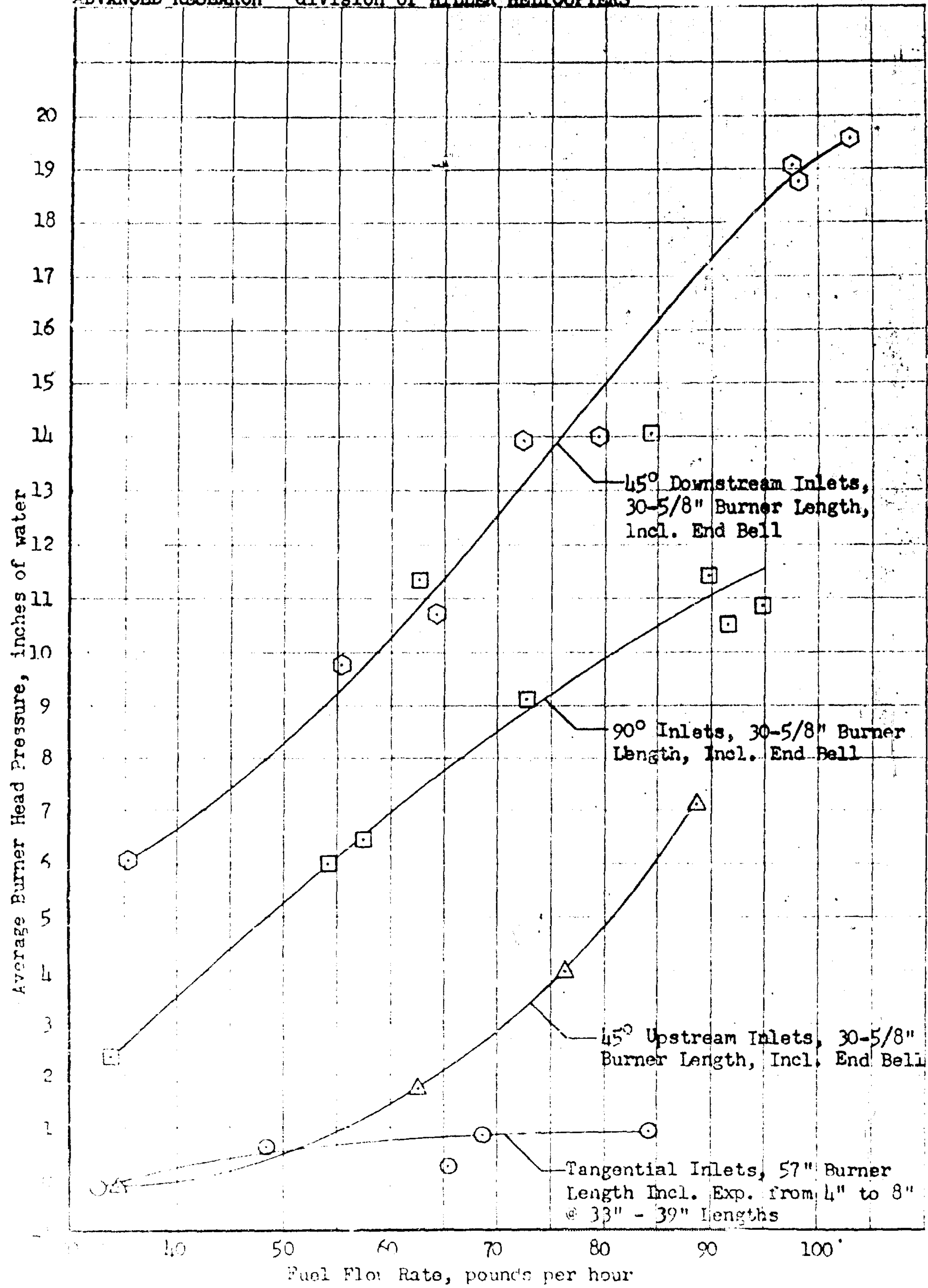

... 4: AVERAGE BURNER HEAD PRESSURE VS FUEL FLOW RATE, VARIOUS INLET ... DIRECTIONS

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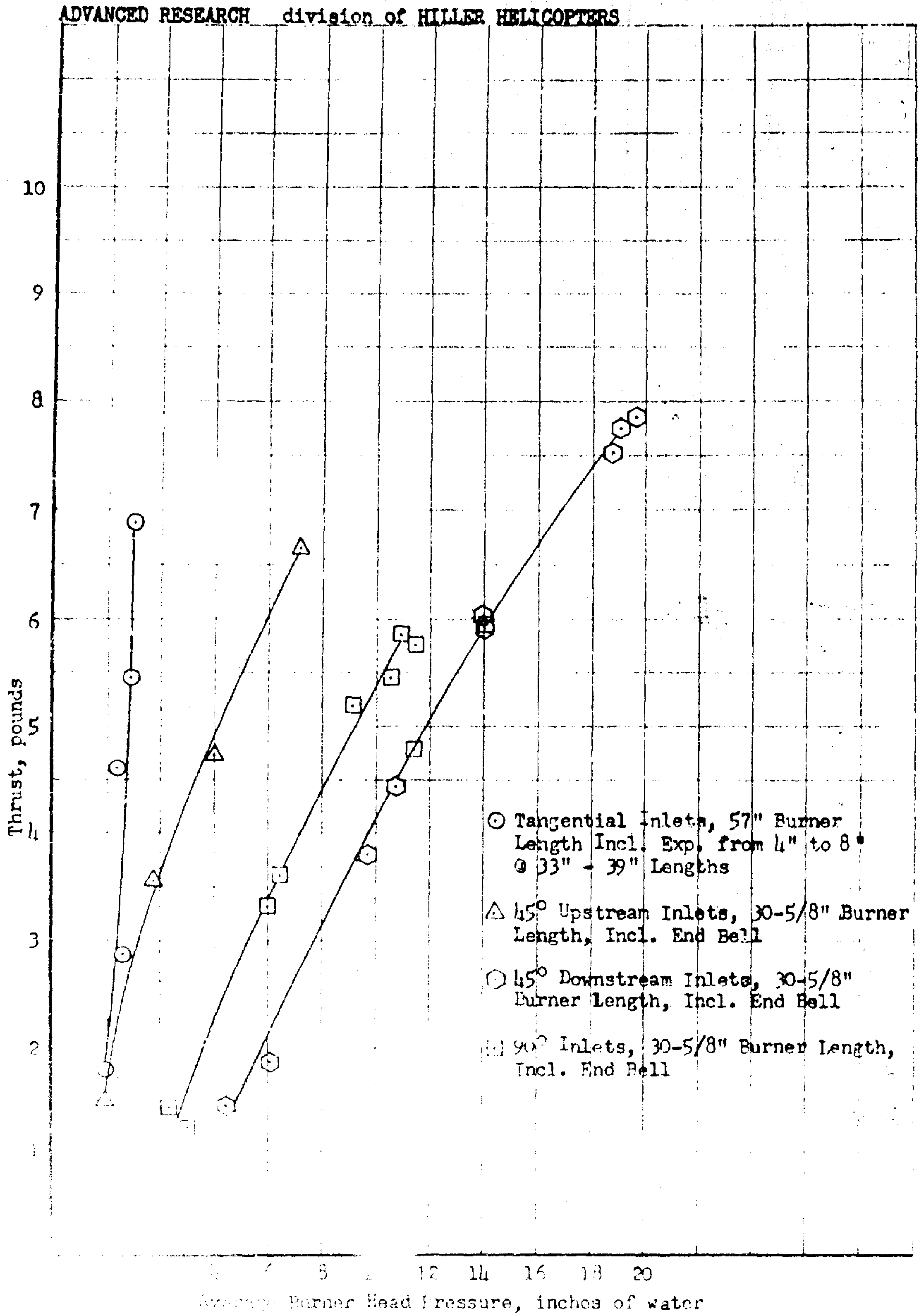

VS THRUST, VARIOUS INLET TUBE

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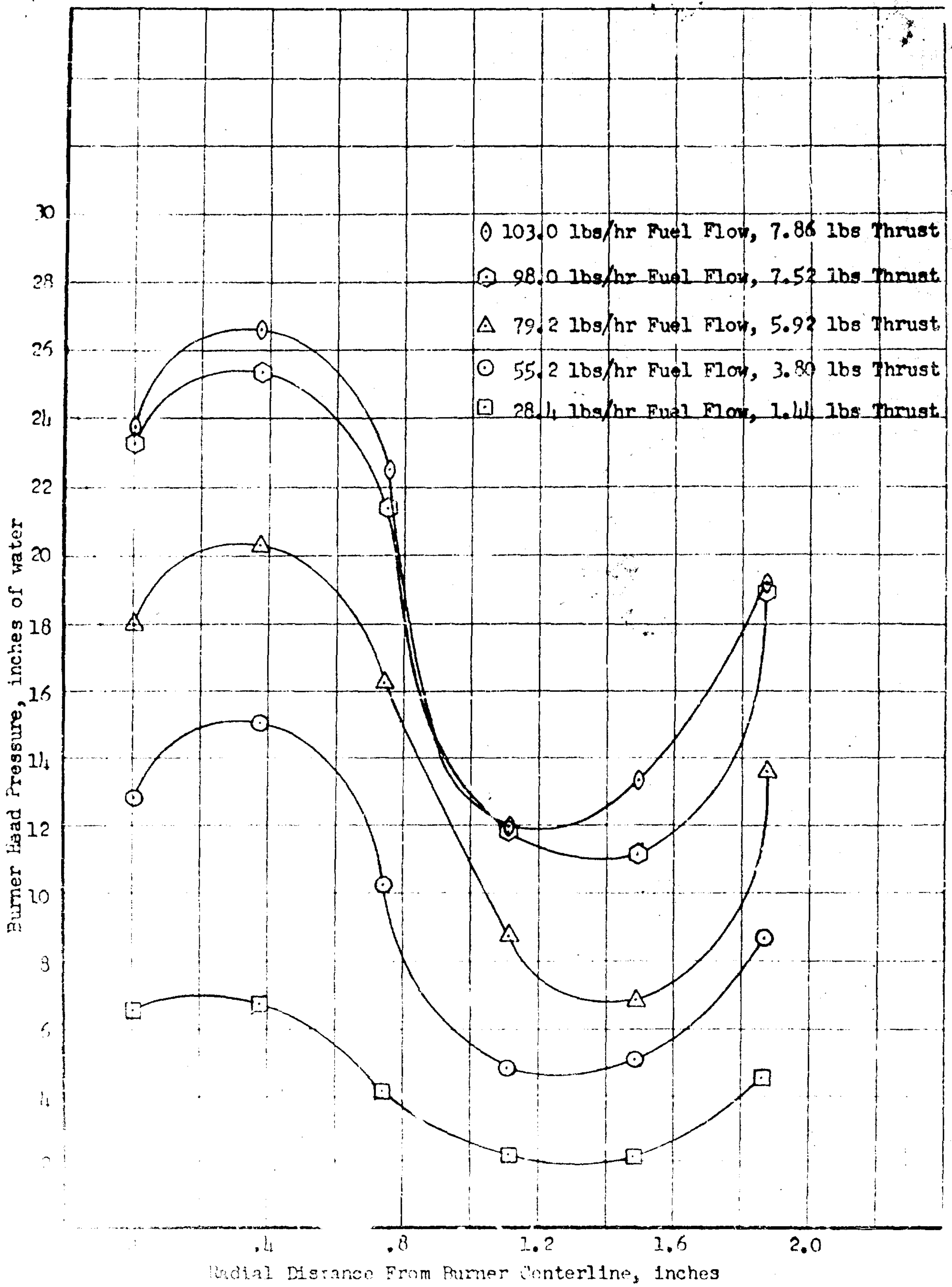

... HEAD PRESSURE VS RADIAL DISTANCE FROM BURNER CENTERLINE,
... INLETS, 30-5/8" BURNER LENGTH, INCL. END BELL

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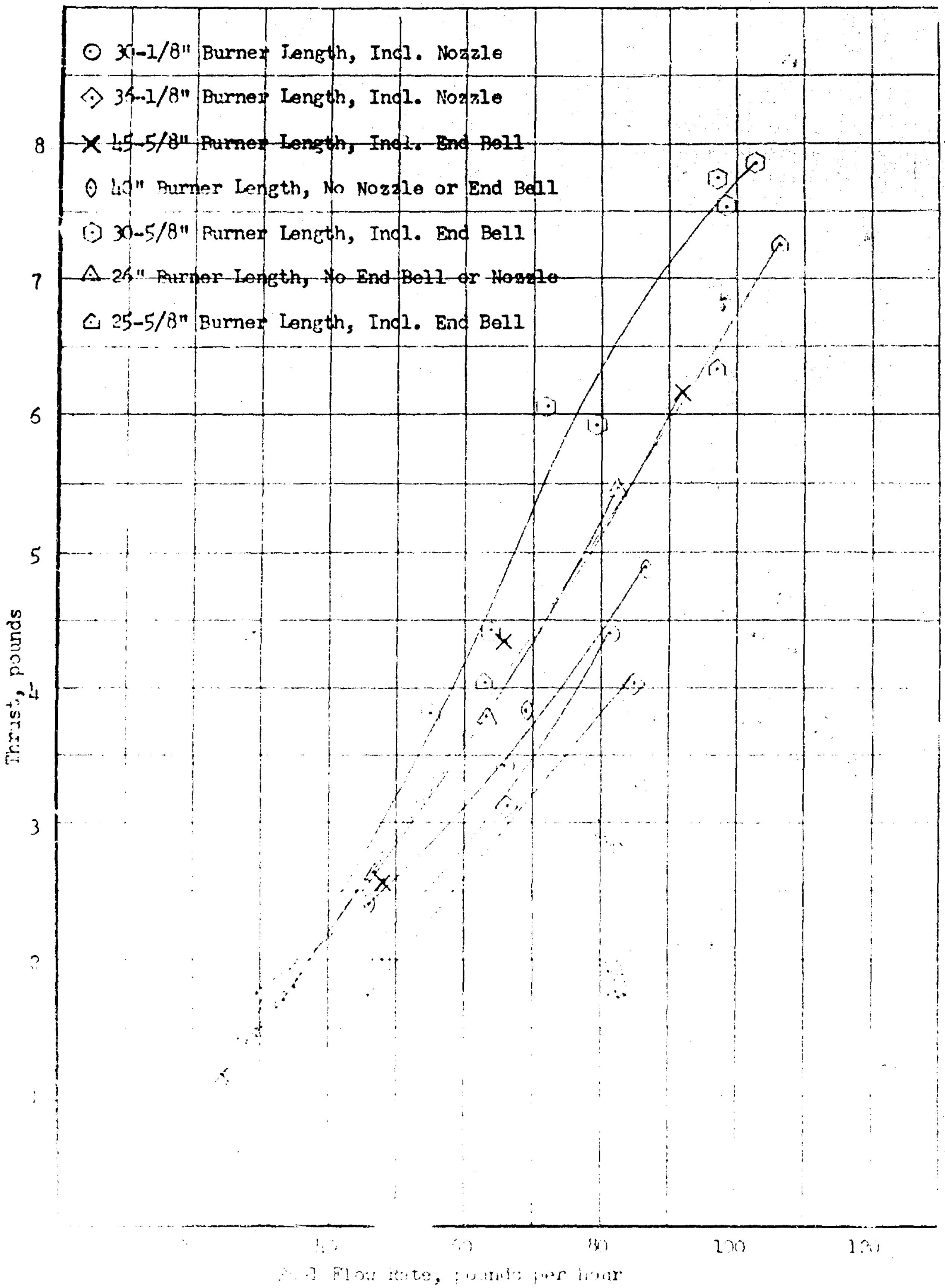

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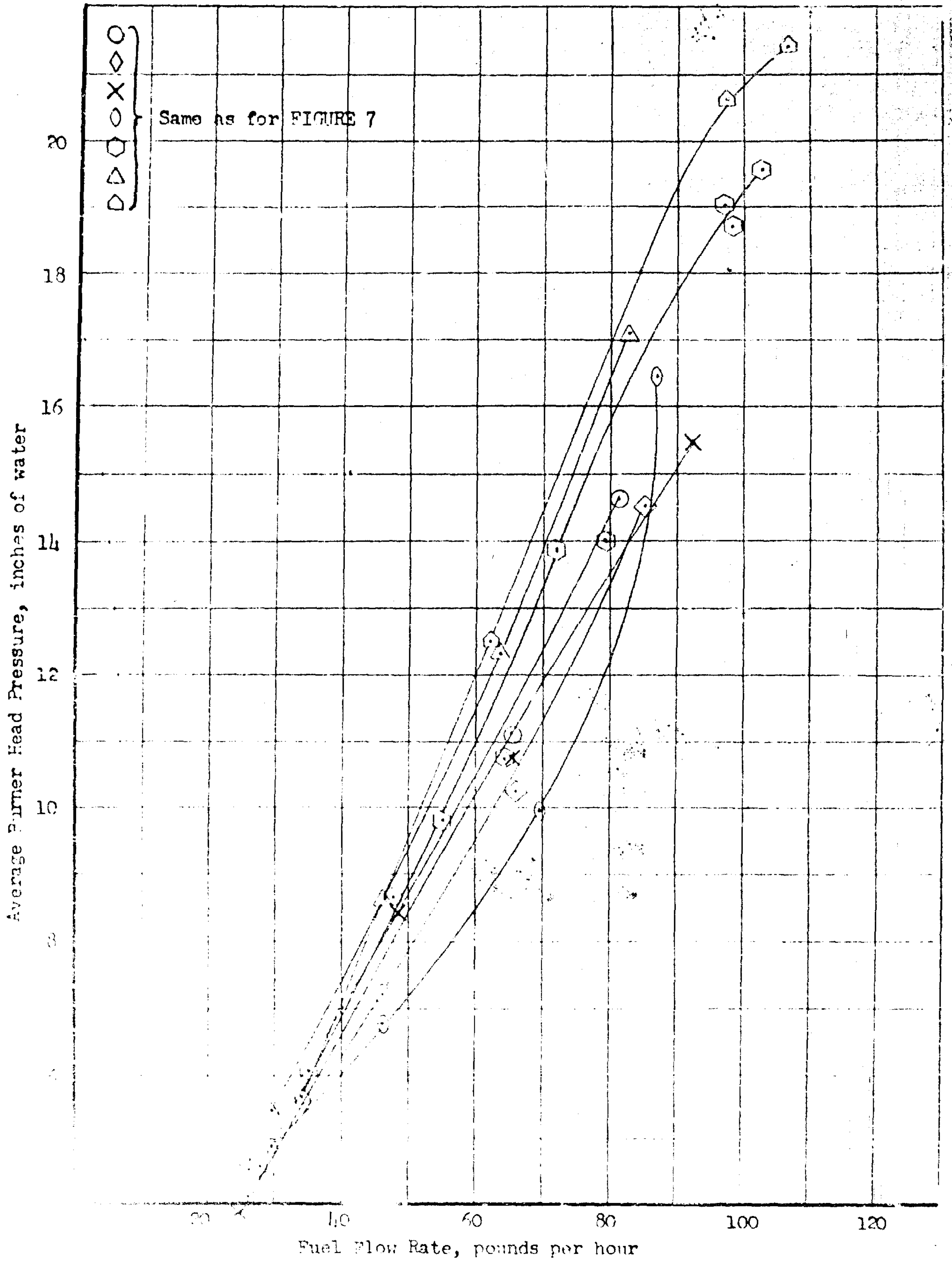

...BURNER HEAD PRESSURE VS FUEL FLOW RATE, VARIOUS CONFIGURATIONS
...UPSTREAM INLETS

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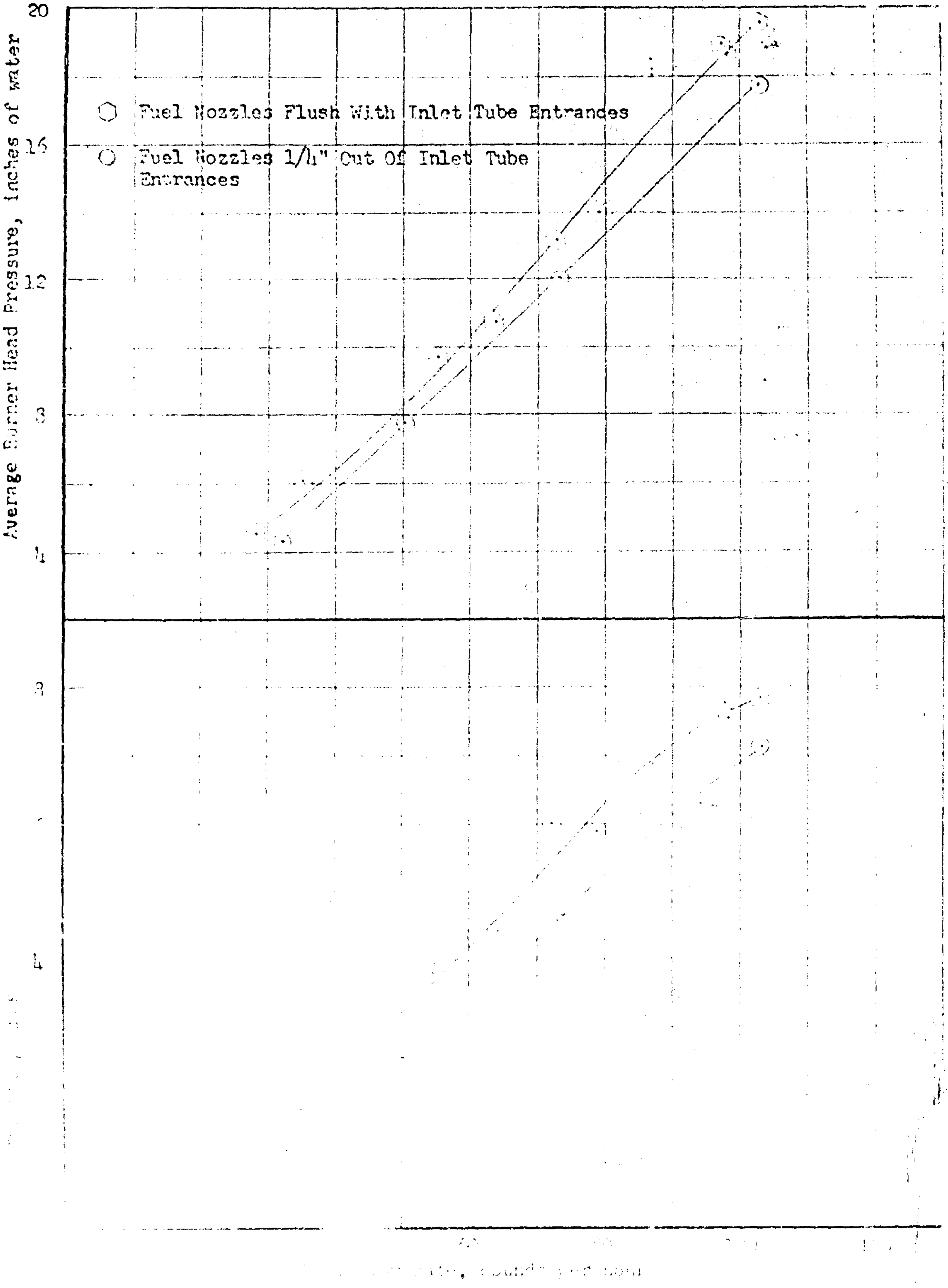

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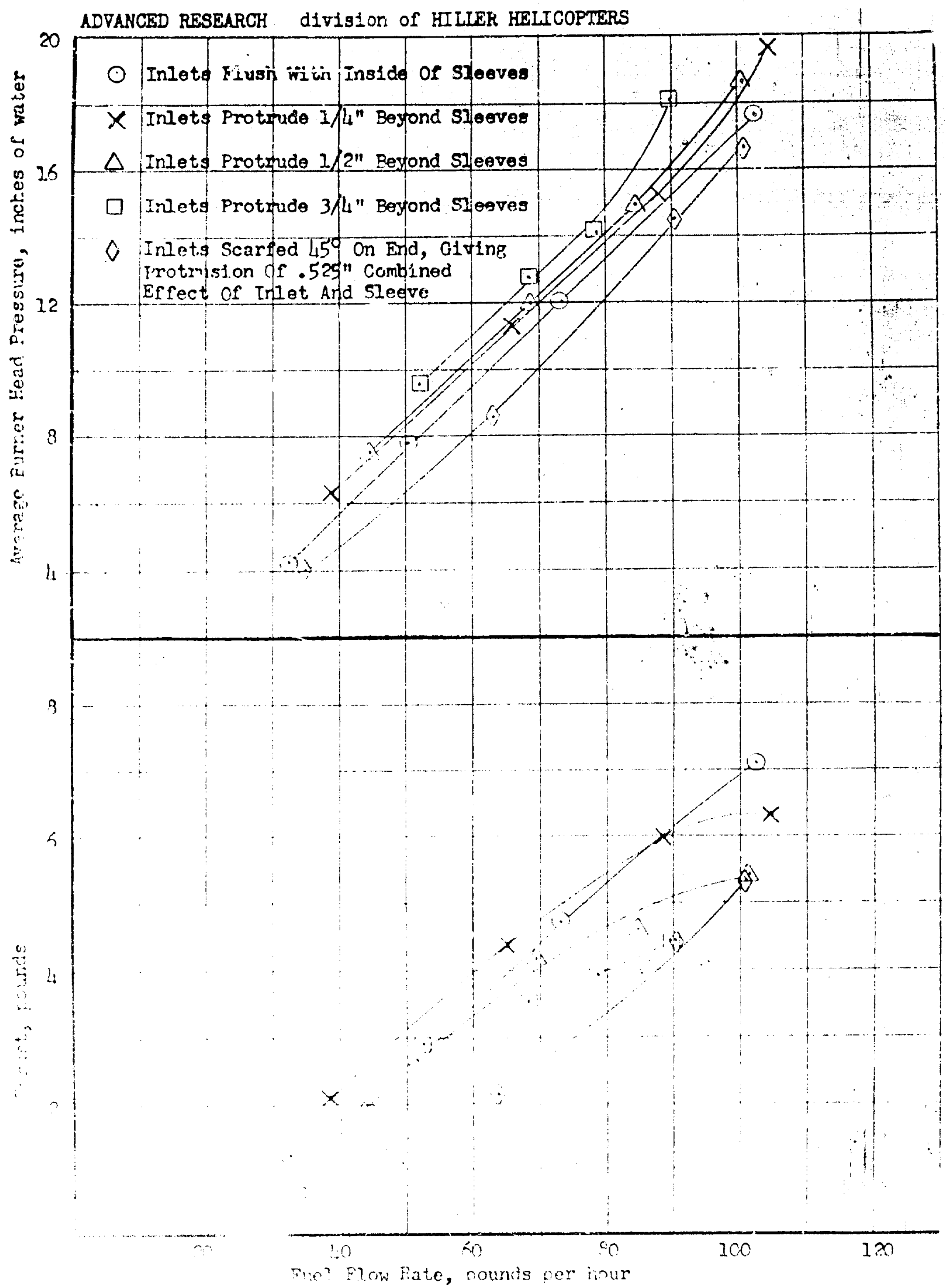

AVERAGE BURNER HEAD PRESSURE VS FUEL FLOW RATE, 45°
INLETS, VARIOUS DEGREES OF INLET TUBE PENETRATION

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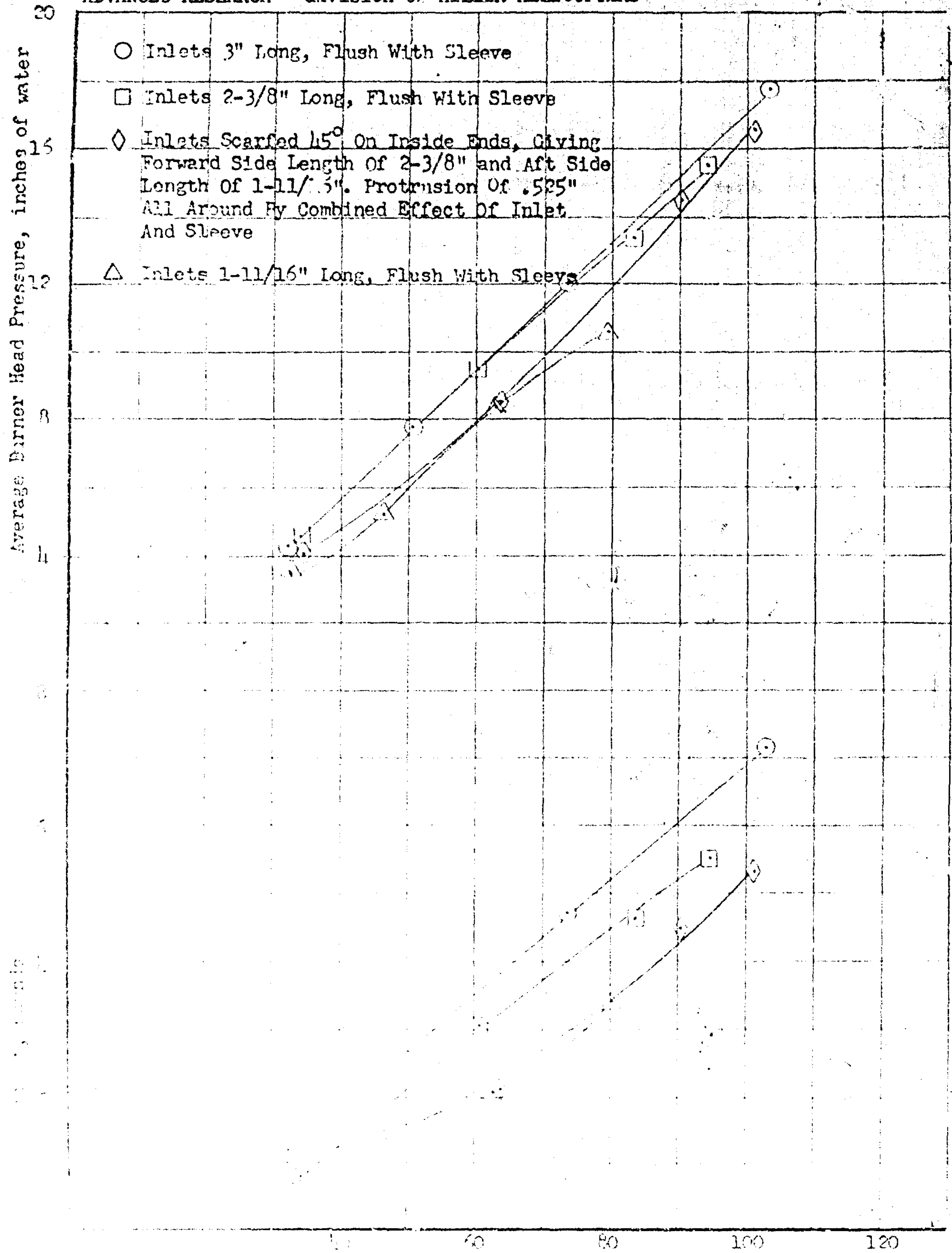

[illegible] RE VS FUEL FLOW RATE, 45° [illegible]

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